# Simulation study on the impact of a single plasma accelerator stage to existing free-electron lasers

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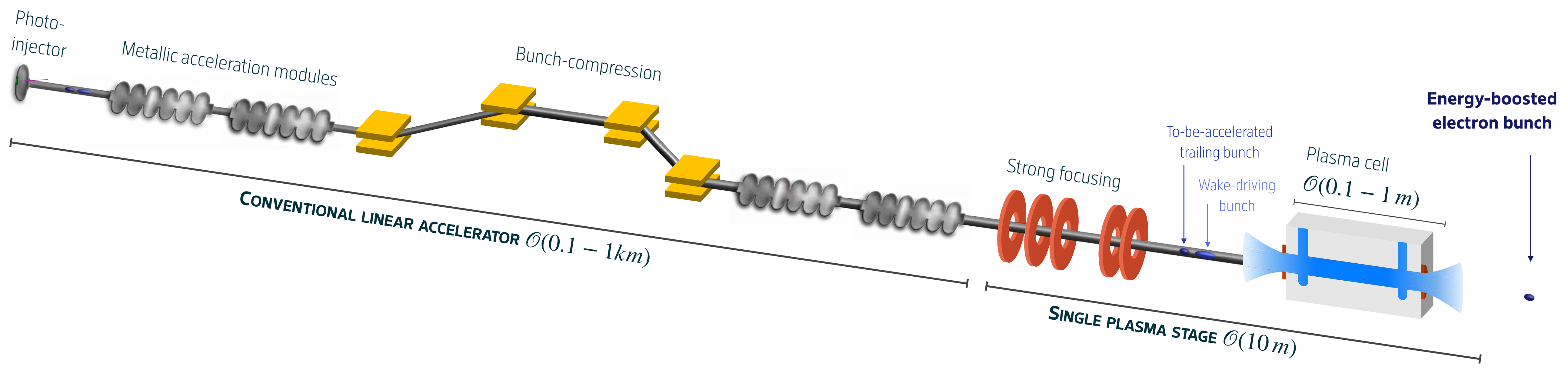
**A plasma-based energy booster to an existing free-electron laser is an essential first application to demonstrate maturity of this novel accelerator technology.**




**Bunch characteristics:**

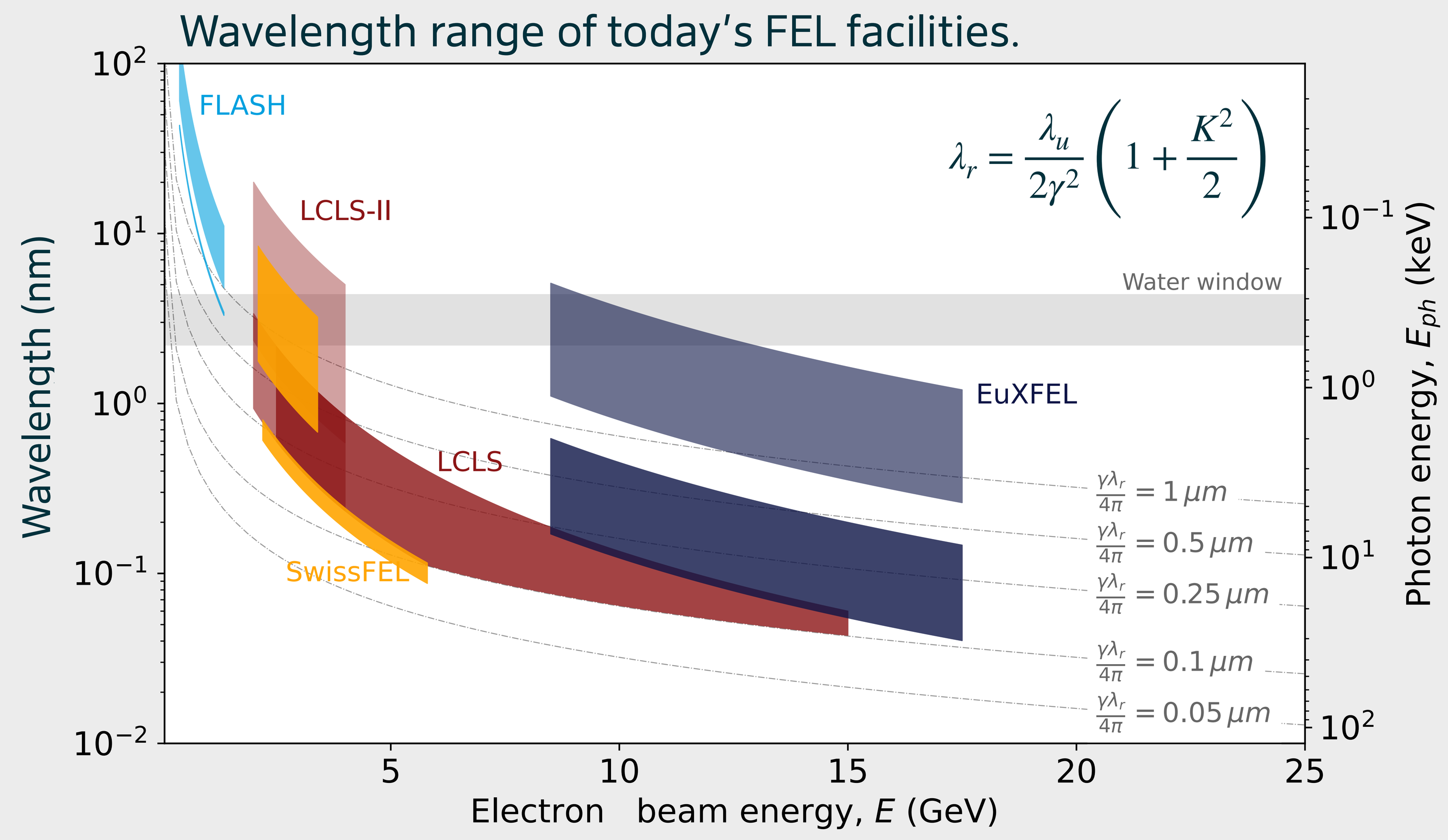
- Bunch duration: ~100 fs rms.
- GeV-level electron energy.
- Bunch charge: $\mathcal{O}(0.1-1\,nC)$.
- Potential MW-level average power.

## Potential impact of an energy booster

- Reaching shorter X-Ray wavelength,
  e.g., FLASH could cover the full water window (with both beam lines).
  e.g., LCLS-II wavelength range could be largely extended.
- Parallel operation of beam lines at different beam energies,
  e.g., boosting the high-gain beam lines of SwissFEL and EuXFEL when operating at low energies enhances user flexibility.
- Compensation for gradient reduction in SRF acceleration structures when operating in CW mode (FLASH, EuXFEL).

Challenges: $\epsilon_n \overset{!}{<} \frac{\gamma\lambda_r}{4\pi} \propto \frac{1}{\gamma}$ $\sigma_\delta \overset{!}{<} \rho \propto \left(\frac{I_{peak}}{\gamma^3\sigma_x\sigma_y}\right)^{1/3}$ $L_{sat} \propto \frac{1}{\rho} \propto \gamma$

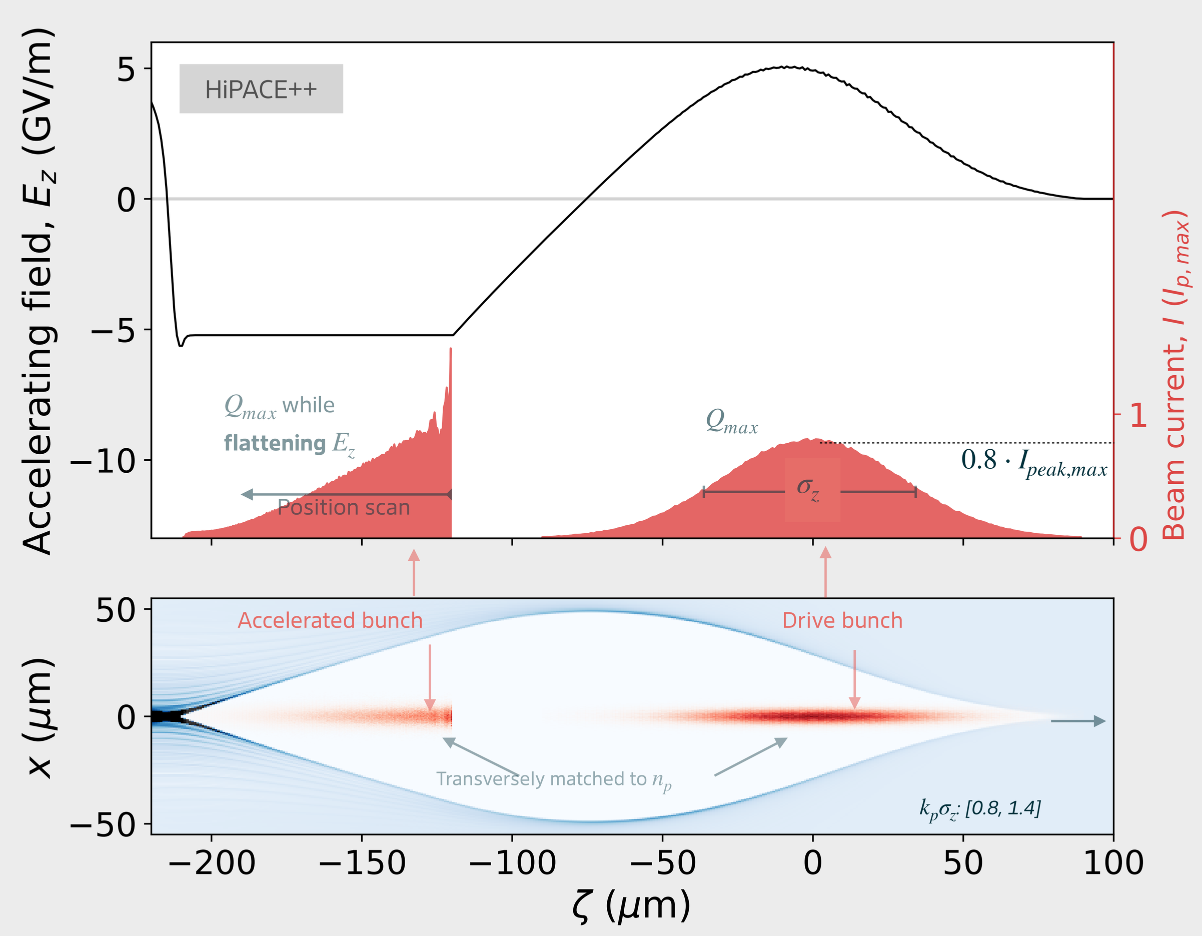
Wavelength range of today's FEL facilities.




## Reach of a single plasma stage — a rudimentary simulation estimate

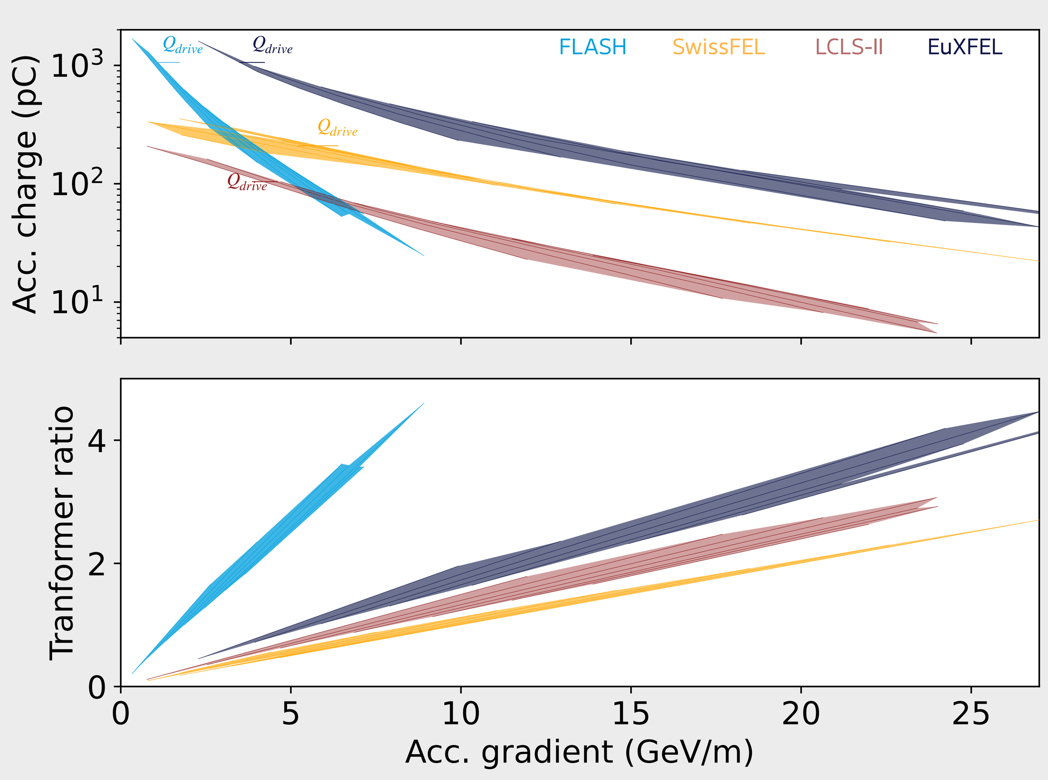
**Methodology of simulation study**

*I. Drive beam ≙ available beam at facility with:*
*a. Maximum charge, maximum energy.*
*b. 80% maximum peak current.*
*II. Scanning trailing bunch position (∝ acc. gradient).*
*a. Field flattening via bunch current shaping.*
*b. Maximising charge.*
*III. Scanning plasma density, $k_p\sigma_z$: [0.6, 1.8].*




Stringent demands are placed on the bunch generation:

| | Charge (nC) | | Peak current (kA) | | Bunch length (µm) | | Bunch Sep. (µm) | Emittance (µm) |
|---|---|---|---|---|---|---|---|---|
| | $Q_{acc}$ | $Q_{drive}$ | $I_{p,acc}$ | $I_{p,drive}$ | $\Delta\zeta(I>100A)$ | $\sigma_{\zeta,drive}$ | $\lvert\mu_{drive}-\mu_{acc}\rvert$ | $\varepsilon$ |
| FLASH | [0.3, 1] | 1 | [2, 3.5] | 2 | [70, 220] | 60 | [200, 250] | 0.5 |
| SwissFEL | [0.050, 0.3] | 0.2 | ~3 | 0.8 | [25, 40] | 12 | [35,45] | 0.1 |
| EuXFEL | [0.1,1] | 1 | [4, 8] | 6 | [40,150] | 30 | [100, 150] | 0.1 |
| LCLS-II | [0.01, 0.2] | 0.1 | ~2 | 0.8 | [30,40] | 10 | [35, 40] | 0.1 |




Aiming at different accelerated bunch charges:

| $Q_{acc}=Q_d$ | $E_{acc}$ (GeV/m) | TR | $L_{dep}$ (m) |
|---|---|---|---|
| FLASH | 1 | 0.5 | 0.7 |
| SwissFEL | 5 | 0.5 | 0.6 |
| EuXFEL | 4 | 0.7 | 3 |
| LCLS-II | 4 | 0.5 | 0.5 |

| $Q_{acc}=1/2\,Q_d$ | $E_{acc}$ (GeV/m) | TR | $L_{dep}$ (m) |
|---|---|---|---|
| FLASH | 2 | 1.5 | 2 |
| SwissFEL | 10 | 1 | 0.6 |
| EuXFEL | 7 | 1 | 2 |
| LCLS-II | 8 | 1 | 0.5 |

### Conclusions

- A single-stage plasma booster in an FEL has various use-cases.
- FLASH, LCLS-II and EuXFEL are prominent candidates for a plasma booster.
- Bunch generation and shaping is a critical aspect to be studied in greater detail.
- Optional operation schemes for a booster may reduce technical demands.

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